

Extremely Compact Massive Galaxies at $1.7 < z < 3$

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Abstract We measure and analyse the sizes of 82 massive ($M \geq 10^{11} M_{\odot}$) galaxies at $1.7 \leq z \leq 3$ utilizing deep HST NICMOS data taken in the GOODS North and South fields. Our sample provides the first statistical study of massive galaxy sizes at $z > 2$. We split our sample into disk-like (Sérsic index $n \leq 2$) and spheroid-like (Sérsic index $n > 2$) galaxies, and find that at a given stellar mass, disk-like galaxies at $z \sim 2.3$ are a factor of 2.6 ± 0.3 smaller than present day equal mass systems, and spheroid-like galaxies at the same redshift are 4.3 ± 0.7 times smaller than comparatively massive elliptical galaxies today. We furthermore show that the stellar mass densities of very massive galaxies at $z \sim 2.5$ are similar to present-day globular clusters with values $\sim 2 \times 10^{10} M_{\odot} kpc^{-3}$

1 Introduction

One of the most exciting discoveries in extragalactic astronomy in the last few years is that massive ($M \geq 10^{11} M_{\odot}$) galaxies at $z > 1$ were extremely compact ([1]; [2]). Since these objects are not found in the local Universe ([3]) it is clear that significant growth in the sizes of these galaxies has occurred during cosmic history.

How these compact galaxies form and evolve is not understood. Models suggest that at very early times galaxies contain large amounts of cold gas, resulting in efficient starbursts (e.g., [4]). As star formation occurs, the gas in these galaxies becomes heated and removed due to various feedback processes, leading to reduced star formation rates, creating compact and massive remnants that are very poor in gas. This way, “dry mergers” are expected to be the dominant mechanism for size and stellar mass growth for these objects [5]. At $z > 2$, however, our knowledge of the size evolution of the most massive objects is much more scarce. There are only a few attempts to explore this issue using small samples of massive galaxies at

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$z \sim 2.5$ (e.g. [6]). With the aim of substantially increase our knowledge of the size evolution of massive galaxies in at this redshift we analyzed a sample of 82 massive galaxies [7] that reveal a continual decrease in galaxy size at $z > 2$.

2 Our Sample: GOODS NICMOS Survey (GNS)

The GOODS NICMOS Survey (NGS) (PI C.J. Conselice) is a large HST NICMOS–3 camera program of 60 pointings centered around massive galaxies at $z = 1.7 - 3$ at 3 orbits depth, for a total of 180 orbits in the F160W (H) band. Each tile ($52'' \times 52''$, $0.203''/\text{pix}$) was observed in six exposures combined to produce images with a pixel scale of $0.1''$, and a Point Spread Function (PSF) of $\sim 0.3''$ Full Width Half Maximum (FWHM). We optimized our pointings to obtain as many high-mass galaxies as possible. These galaxies consist of Distant Red Galaxies, IEROs and BzK galaxies ([7]). Within our NICMOS fields we find a total of 82 galaxies with masses larger than $M \geq 10^{11} h_{70}^{-2} M_{\odot}$ with photometric and spectroscopic redshifts in the range $1.7 \leq z \leq 3$. In addition to these data, and to allow a comparison with the sizes obtained in the H-band, we measure, whenever possible, the sizes of the same galaxies using the z-band (F850LP, 5 orbits/image) HST ACS data. The z-band data is drizzled to a scale $0.03''/\text{pix}$ and has a PSF FWHM of $\sim 0.1''$. Limiting magnitudes reached are $H = 26.8(5\sigma)$ and $z = 27$ (10σ in a 0.2 aperture) [8].

3 Results

Masses and photometric redshifts of our galaxy sample, although we have some spectroscopic ones, are derived from standard multi-color stellar population fitting techniques (e.g., [9]), using filters BVRiIzJHK. In particular, our stellar masses are calculated by assuming a Chabrier Initial Mass Function (IMF) and producing model Spectral Energy Distributions (SEDs) constructed from Bruzual & Charlot [10] stellar populations synthesis models. Galaxy sizes were measured using the GALFIT code [11]. We check in addition the structural parameters using ACS data [8], utilizing simulations [12] on our ability to recover and measure these systems.

We present the stellar mass-size relation of our sample in Fig. 1. The first redshift bin allows a comparison with previous work [13]. Overplotted on each panel is the local value of the half-light radii, and its dispersion, at a given stellar mass [3] from Sloan Digital Sky Survey. Remarkably, none of our galaxies at $z > 1.7$ fall in the mean distribution of the local relation, and only three would match if the masses were overestimated by a factor of two.

To quantify the observed size evolution we show the ratio between the sizes we measure, and the measured sizes of nearby galaxies at the same mass, as a function of redshift (Fig. 2), using again the SDSS [3] as the local sample. We fit the evolution of the decrease in half-light ratio with redshift as a power-law $\sim \alpha(1+z)^{\beta}$,

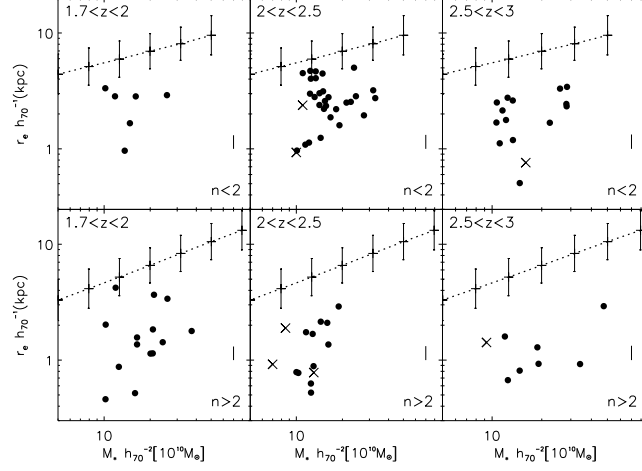


Fig. 1 Stellar mass-size distribution for our sample. Overplotted are the mean and the 1σ dispersion of the distribution of the Sérsic half-light radius of SDSS as a function of stellar mass [3] and the crosses are the galaxies from [6] whose masses have been converted to our Chabrier IMF. For clarity, individual error bars are not shown for our data, but a typical size error bar is shown in the right side of each bin. This mean size relative error is 0.04'' which is 0.32 kpc at $z=2.5$. Uncertainties in the stellar masses are ~ 0.2 dex.

where we calculate that for the disk-like galaxies $\beta = -0.82 \pm 0.03$, and for the spheroid-like systems $\beta = -1.49 \pm 0.04$.

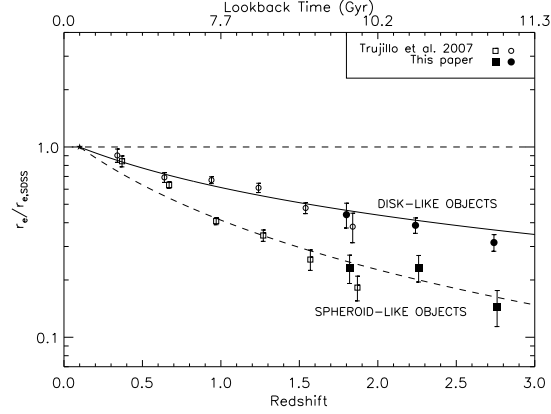


Fig. 2 Size evolution of massive galaxies ($M > 10^{11} M_{\odot}$) with redshift. Plotted is the ratio of the median sizes of galaxies in our sample with respect to sizes of nearby galaxies in the SDSS [3] local comparison (solid points). The results of [13] for systems at $0.2 < z < 2$ are overplotted (open symbols). The error bars indicate the uncertainty (1σ) at the median position.

4 Discussion

As has been demonstrated in previous work, many massive galaxies at $z < 2$ appear to grow in size by up to an order of magnitude (e.g., [13]). An interesting question is whether these massive galaxies become progressively smaller at higher redshifts, containing possibly even smaller sizes at $z > 2$. Our results provide the first statistical sample in which to answer this question. As seen in Fig. 2, the objects in our sample are compatible with the idea that the size evolution reaches a plateau beyond $z = 2$. In this plot, the significance of evolving to smaller sizes is 2.2σ for disks, and 1.8σ for spheroids. To shed some light on this question we compute the stellar mass density of our galaxies and compare these to the densest collection of stars in the local Universe – globular clusters.

A typical spheroid-like galaxy in our sample at $z \sim 2.75$ has a stellar mass of $\sim 2 \times 10^{11} M_{\odot}$, and a size of $r_e \sim 1$ kpc. The stellar density for this object, assuming spherical symmetry, is $\rho = (0.5M)/(4/3\pi r_e^3) \sim 2.4 \times 10^{10} M_{\odot} \text{kpc}^{-3}$. A disk-like galaxy at $z \sim 2.75$ has a typical mass of $\sim 2 \times 10^{11} M_{\odot}$ and size $r_e \sim 2$ kpc. Assuming a disk symmetry, the stellar mass density within these disk-like systems is $\rho = (0.5M)/(\pi r_e^2 h) \sim 2.6 \times 10^{10} M_{\odot} \text{kpc}^{-3}$, where we have used $h \sim 0.3$ kpc. In both cases the stellar mass densities are similar. A typical globular cluster ($r_e = 10$ pc and $M \sim 10^5 M_{\odot}$) has a density of $\sim 1.2 \times 10^{10} M_{\odot} \text{kpc}^{-3}$. This is remarkably similar to our massive galaxies at $z > 2$, and reveals that these high- z galaxies may in principle have an origin similar to globular clusters. These high densities also suggest that their stellar mass densities likely do not become much larger at high redshifts ($z > 3$). A massive galaxy at $z > 2$ must have formed very quickly, and these high stellar densities could reflect the high gas densities in the primeval Universe.

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